Renewable and Sustainable Energy Reviews 34 (2014) 596–607

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Optimal power flow analysis of a Switzerland's transmission system for long-term capacity planning

Antriksh Singh *, David Willi, Ndaona Chokani, Reza S. Abhari

Laboratory for Energy Conversion, The Institute of Energy Technology, ML J 33, Sonneggstrasse 3, ETH Zurich, Zurich CH-8092, Switzerland

ARTICLE INFO

Article history:
Received 13 August 2013
Received in revised form
4 March 2014
Accepted 17 March 2014
Available online 9 April 2014

Keywords:
Geographic information systems
Power system modelling
Power grids
Wind energy

ABSTRACT

Optimal power flow modelling of large and complex power transmission networks is an essential tool for investors and policy makers for the development of energy technologies, security, trade, and policy-making. However, an analysis of a country's power system can be impeded by scarcity of operational information. This paper presents an integrated approach of geographically indexed production, demand and grid modelling for large-area power systems. This approach is validated through the accurate identification of transmission lines in Switzerland that have been earmarked for improvement. Furthermore, methods are developed to account for variance in the loading of transmission lines, and physical models are used to accurately model wind-generated electricity. A scenario for the development of wind power in Switzerland is analyzed and it is shown that in prospective regions of wind power development Switzerland's grid is capable in its current state of providing congestion-free dispatch.

Contents

1. Introduction

The fast pace of growth and liberalization of energy markets across Europe has brought the entrance of numerous renewables

* Corresponding author. Tel.: +41 44 632 0905; fax: +41 44 632 1100.
E-mail addresses: singh@lec.mavt.ethz.ch (A. Singh), dwilli@ethz.ch (D. Willi), chokani@lec.mavt.ethz.ch (N. Chokani), rabhari@lec.mavt.ethz.ch (R.S. Abhari).

http://dx.doi.org/10.1016/j.rser.2014.03.044
1364-0321/

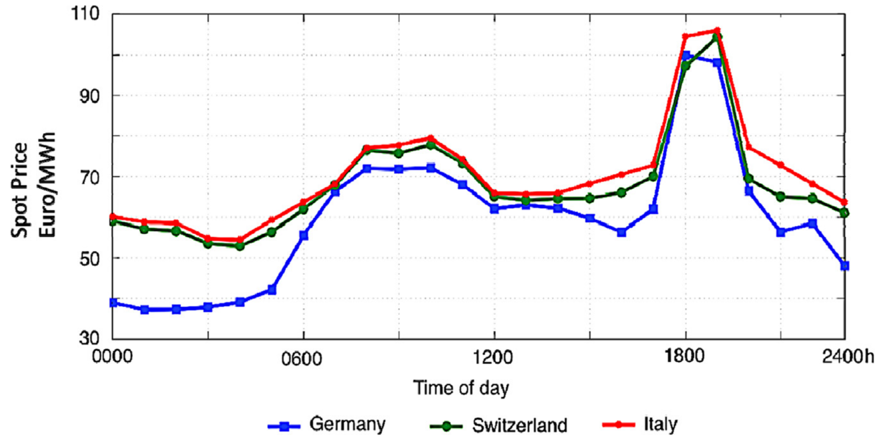

Fig. 1. Hourly spot prices in Germany, Switzerland and Italy on Wednesday, 27.02.2013 (data is from [6]).

Table 1
Projected increase in the installed wind power capacity in Switzerland's neighboring countries.

Country	2010 (MW)	2020 (MW)	Change (%)
Austria	1011	2578	+155
Italy	5800	12,680	+119
France	5542	25,000	+351
Germany	27,526	45,750	+66

utilities. For example, the small land-locked country of Switzerland has approximately 900 independent power utilities. Limits on the growth and siting of renewable energy power plants are often dictated by the operating state of the transmission grid. Power flow analysis enables the operational state and availability of the grid to be quantified. However, this analysis is challenging, since, for commercial and security reasons, limited data about the operation of power systems is publically available. There is therefore interest in developing approximate models that are based on publically accessible information in order to assess the long-term capacity planning of generation and transmission systems.

Several researchers have developed approximate models for different scales of analysis and with varied approaches [1–5]. While these studies have demonstrated the utility of approximate power flow models, it is evident that approximate models with improved fidelity may extend the range of applicability of such models. Thus the objectives of the work are as follows.

1) Develop a more detailed grid assessment framework, based on publically accessible information and tools, for the long-term planning of power generation and transmission capacity.
2) Assess transmission grid networks by modelling spatial and temporal variability in power generation and consumption.

In order to demonstrate this more detailed methodology, Switzerland presents a compelling test case. First, 23% of Europe's electricity flows across Switzerland through more than 40 tie-in points, accounting for large monthly transactions. Second, while large transit traffic across the grid brings Switzerland energy security, it also brings economic benefit from the service charges that are earned from the grid and energy arbitrage opportunities with ample storage potential in the form of pumped-hydrostorage. Fig. 1 shows the hourly spot prices in the Germany–Switzerland–Italy corridor. The complex operation of storage and cross-border trade makes it a challenging case for dispatch modelling.

Third, the future restructuring of the power generation profiles of Switzerland's neighboring countries will signify a substantial growth in wind energy production (Table 1). Fluctuating levels of wind-generated electricity will test the limits of grid capacity, making Switzerland an interesting test case.

The paper is organized as follows. The following section details the methodology adopted for modelling of the elements of power generation, demand and transmission system infrastructure. Subsequently, the optimal power flow simulation results of Switzerland's transmission network are presented, in order to further demonstrate the model's capabilities for grid expansion planning. Following this, a scenario of increasing wind power in Switzerland is developed and discussed. The paper then concludes with key observations from the work.

2. Methodology

The present work utilizes a GIS-integrated approach that is developed for the spatial and temporal modelling of power generation, transmission and consumption across one or more transmission zones in large interconnected systems. This is achieved by extending the capabilities of MATPOWER, a MATLAB-based power systems simulation tool [7] within our integrated GIS-based tool for large-area econometric assessment of wind power development, windSeeker [8–11]. For this work, datasets were obtained from government, utility or public web archives. Missing infrastructural and operational data was supplemented by data procured from the European Network of Transmission System Operators for Electricity (ENTSO-E) [12]. A geographically indexed database was created by manually geo-referencing the elements of the analysis for the year 2011.

2.1. Modelling power system elements

In Switzerland, the Swiss Federal Office of Energy—Bundesamt für Energie (BfE)—makes data relating to power generator infrastructure and historical operation data [13] publicly available. The power systems data was developed by manually geo-referencing data for Switzerland, as shown in Fig. 2. The figure shows the geographical locations of generation plants and substations. These locations are overlaid on a contour map of the spatial distribution of electricity consumption. Also shown are Switzerland's transmission grid network and transformer units. The characteristics of the elements are summarized in Table 2.

Using this dataset, a 'power-island' model was implemented to simulate power flows in the transmission network. At any given instant, the following rules are applied.

1) Generators dispatch power to the geographically closest substation.
2) Each substation acts as an isolated balancing unit or 'island'.

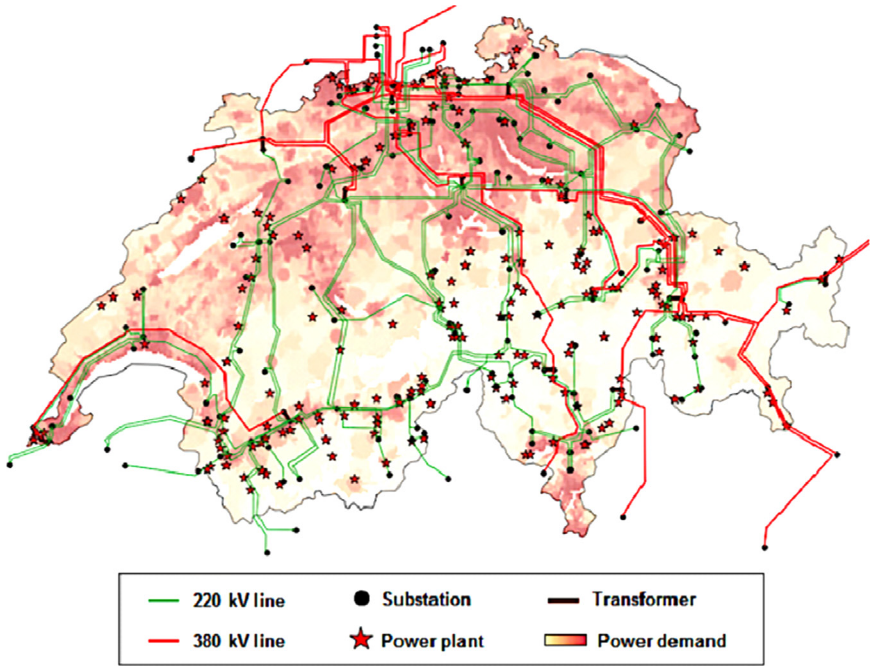

Fig. 2. Map showing Switzerland's power infrastructure, network topology, and spatial distribution of power demand.

Table 2
Characteristics of elements in power systems data developed for power flow analysis of Switzerland's network.

Type	Length/number
Transmission grid	
380 kV	4900 km
220 kV	1800 km
Generators	
Thermal	10
Nuclear	4
Hydro	181
Bio	Negligible
Substations	
380 kV	34
220 kV	127
Transformers	
380 kV/220 kV	14

3) Substations satisfy local demand via distribution network (line ratings < 110 kV)
4) If a substation has excess power, the excess power is circulated across the network to substations with a power deficit; or
5) if a substation has power deficit, power is received from the network to make up the deficit.
6) Transactions to neutralize power deficit or excess are achieved across the transmission network (line ratings > 110 kV).
7) Substations within a Switzerland's transmission system can transact between themselves, as well as with substations in other transmission zones (national and international).
8) The transmission network is composed of substation nodes, which are connected by transmission lines in a hybrid topology [14].

Fig. 3 schematically depicts the 'power island' approach and shows its GIS implementation in southern Switzerland. The 'islands', or zones of balance, are created by dividing up the geographical area using a Voronoi tessellation [26,27] seeded on substations. If '*S*' is the set of '*n*' substations in the country, a Voronoi tessellation of '*S*' divides the area of Switzerland into '*n*' islands, one for each site, such that any generator '*g*' enclosed in an island dispatches generated electricity to the substation within the island. This approach facilitates the geographical aggregation of generators that feed power to a substation. The simulated sum of power generation in island '*i*' at any time '*t*' will follow (1) in optimal power flow analysis, which requires demand and international cross-border flows as the boundary condition for island '*i*' in order to calculate generation from each generator

$$ {}_t^i\Sigma(Generation)_g = {}_t^i\Sigma(Demand) + {}_t^i\Sigma(Crossborder\ flows)_{international} + {}_t^i\Sigma(Crossborder\ flows)_{national} \quad (1) $$

In the following sub-sections, a brief description of the key power flow model elements (lines, generators, loads, etc.) is provided, along with a description of their treatment in the present work. The MATPOWER package comes with pre-defined model implementations for the elements, and the data-structures available in the package provide the flexibility to define each of the elements individually.

2.1.1. Transmission line model

The data for the transmission lines, including lines and transformers, was manually developed by geo-referencing the transmission lines map available from the web archives of Switzerland's transmission system operator, Swissgrid [15]. The overhead lines and transformers in the network are modelled in MATPOWER as standard π-transmission lines with series impedance and shunt admittance. Relevant electrical properties for three voltage ratings used in the model are presented in Table 3. The properties for other rating elements are interpolated from Table 3.

To accurately model a line's capacity it is essential to know the number of phases and parallel circuits on the pylons that constitute each line. These parameters were obtained for each line from the ENTSO-E grid map [17]. The properties for lines are then lumped and classified based on voltage ratings, and identified as single lines between two substations (Fig. 3). Transformers are modelled as lossless conversion units to provide cross-connection between circuits of different voltage ratings. Since most transmission lines

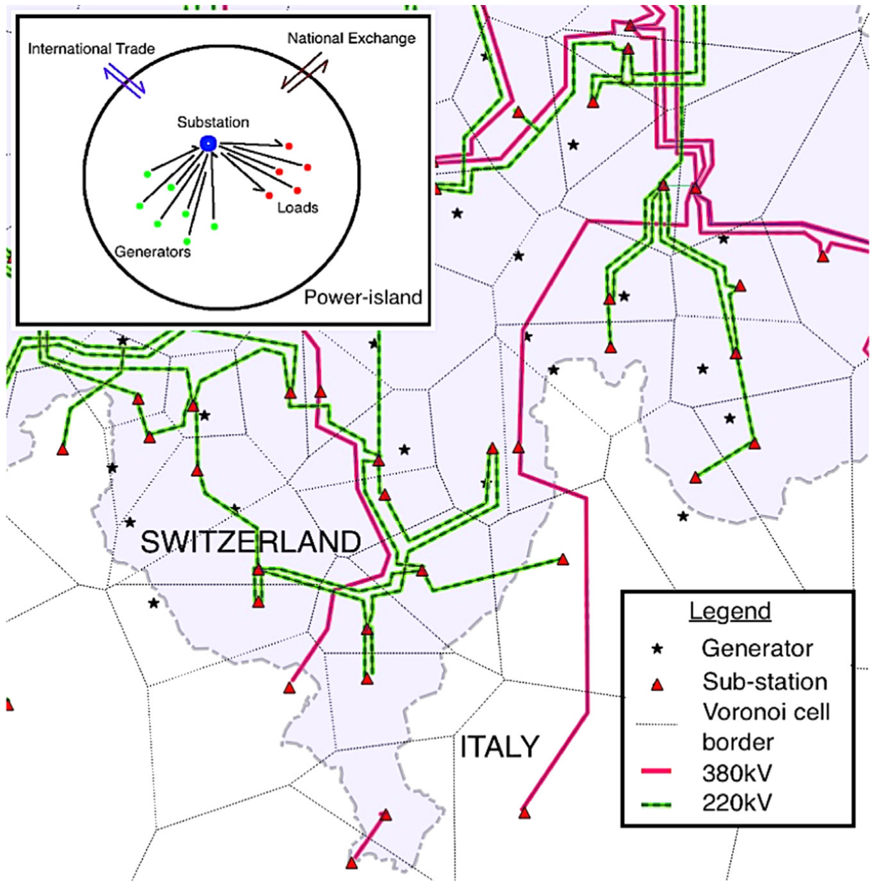

Fig. 3. Schematic representation of a GIS-based power island approach for definition of local power-balance zones.

Table 3
Electrical properties used for the transmission line model [16].

Rated voltage	230 kV	345 kV	500 kV
R (Ω/km)	0.050	0.037	0.028
$X_L = \omega L$ (Ω/km)	0.488	0.367	0.325
$B_C = \omega C$ (μS/km)	3.371	4.518	5.20

Table 4
Operational and physical line operating limits used in the transmission line model [16].

Rated voltage	220 kV	380 kV	750 kV
Peak operating voltage (kV)	245	420	765
Thermal power limit (MVA)	340	1380	5600
Surge impedance load (MW)	135	500	2170

in Switzerland are less than 80 km in length, capacitive effects are assumed to be negligible. Moreover, as geographical and operational data for line conditioning elements (phase-shifter, line switches, etc.) are unavailable, they are neglected in the analysis.

2.1.2. Line operating limits

High-voltage transmission lines have certain operating limits. Table 4 shows the operational and loading limits that are used in the transmission line model.

For the analysis of Switzerland's transmission network, the thermal limit is chosen as the constraint for the maximum allowable power flow, as most lines are less than 80 km in length. In practice,

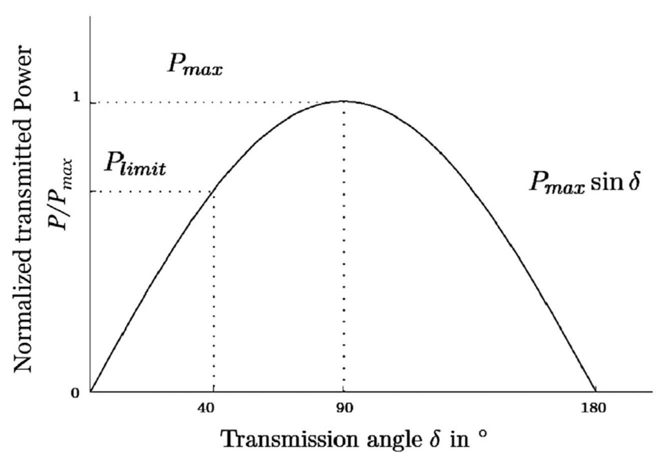

Fig. 4. Transmitted active power as a function of the transmission angle [16].

transmission lines are operated with a safety factor or reliability margin. Fig. 4 shows the theoretical dependence of electrical phase shift on the active power at the receiving end of a line. P_{limit} indicates the maximum received power, for which a reliability margin of at least 30% is maintained. Therefore, in the absence of line conditioning elements (phase shifters, switches, etc.) the allowable phase shift constraint in simulations is specified as 40°.

2.2. Electricity demand model

It is highly important when conducting power flow simulations to ensure that the input and boundary conditions are as realistic as

possible. One of the inputs into the simulations is the instantaneous power demand at a substation. Time series histories of aggregate power demand for Switzerland at 15-min intervals are available from the transmission grid operator, Swissgrid.

When estimating the loading at substations, which is equivalent to modelling the spatial distribution of electricity consumption, the following assumptions were used.

1) The demand from households in a given area is proportional to the population of that area.
2) The spatial distribution of population is spatially correlated to the spatial distribution of workplaces/industries [1].
3) The spatial variance in per capita consumption of electricity is negligible.
4) Population density and electricity consumption in the transportation sector are correlated.
5) Reactive power is assumed to be consumed by all consumers at all times and at fixed proportions to active power, with a constant power factor of 15% [18].

It should be noted, however, that energy intensive industries and grid independent generators could not be modelled due to lack of data. While it is difficult to quantitatively justify all the assumptions, the study [1] with actual consumption and population data from regions in Italy provides an indication of the strength of the assumption (2). A correlation factor of 91% between electricity consumption and population distribution was observed. Such a high correlation might not necessarily be observed in other parts of the world, especially in developing countries where compact regions tend to have high economic disparity. A limiting assumption may be assumption (2), as large industrial loads, such as that of an alumina smelter, may result in a power demand pattern that is not necessarily correlated to the size of the local population. Based on these assumptions, the electricity demand at each substation is modelled as a function of the instantaneous per capita energy consumption, as follows:

$$Energy\ Demand_{substation} = \Sigma_i \left(A^i \times PD^i \times PCE\right) \qquad (2)$$

where 'i' is the index of a pixel in the island of a substation defined by the Voronoi tessellation, A^i is the associated geographical area of the pixel, PD^i is the population density in area A^i, and PCE is the 2011 per capita electricity consumption for Switzerland. The population density map of Switzerland was developed using the GPW v3 database for the year 2010 [19]. The difference between the aggregated population calculated from the GPW dataset and the population of Switzerland [20] is less than 2%, indicating the high accuracy of the population density map. Fig. 2 shows a snapshot of the derived electricity demand in Switzerland at the peak demand time for the year 2011.

2.3. Cross-border flows

European countries are connected via the interconnected European grid; thus they constantly exchange power via imports from and exports to various markets. Fig. 5 shows the cross-border lines between Switzerland and its neighboring countries, with historical cross-border imports and exports for the year 2011.

For the present work, cross-border exchanges across Switzerland's border are imposed as boundary conditions (flow at tie-in points). Historical time series data for Switzerland at 15-min intervals was obtained from the web-archives of Swissgrid, where only the aggregated power flows between the countries were published. In the model, in order to specify the instantaneous loading at each tie-in point, the total cross-border power flow at each international border was distributed among all cross-border lines at that border in the ratio of their thermal limits

$$\frac{FL_{i,\ 220\ \mathrm{kV}}}{FL_{j,380\ \mathrm{kV}}} = \frac{TL_{220\ \mathrm{kV}}}{TL_{380\ \mathrm{kV}}} \qquad (3)$$

$$\textstyle\sum_i FL_{i,220\ \mathrm{kV}} + \sum_j FL_{j,380\ \mathrm{kV}} = Total\ cross-border\ flow \qquad (4)$$

where FL_i denotes cross-border lines between two neighboring countries, and TL_i denotes the thermal limit of a given line rating. It should be noted that in reality cross-border power transactions at the tie-in points are determined by the nodal prices of electricity production.

2.4. Electricity supply modelling

2.4.1. Infrastructure model

Publically available data for the nameplate capacity of power generators was available for more than 90% of the total installed capacity in Switzerland. For generators with a known location and primary driver, but of unknown capacity, the approximate installed

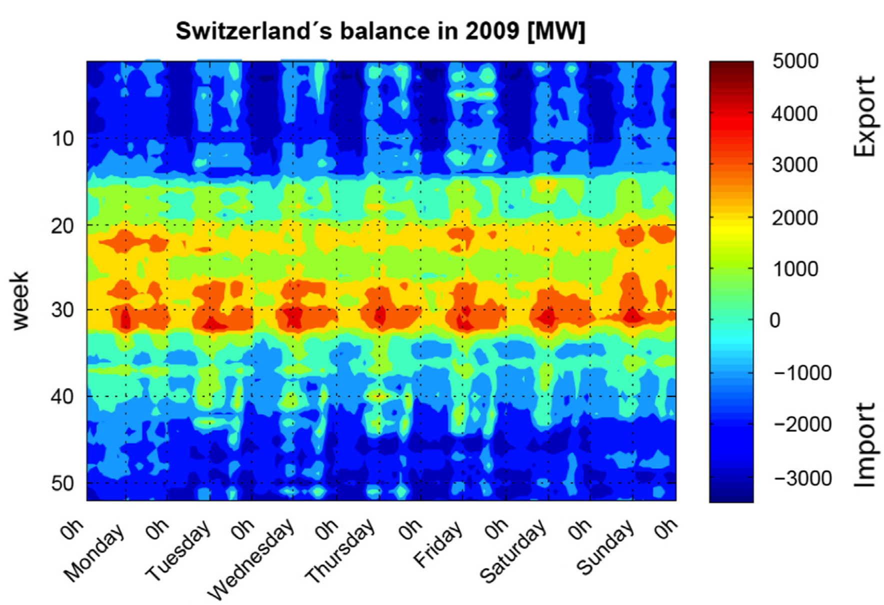

Fig. 5. Daily averaged cross-border exchange across Switzerland's borders in 2011 (data from [21]).

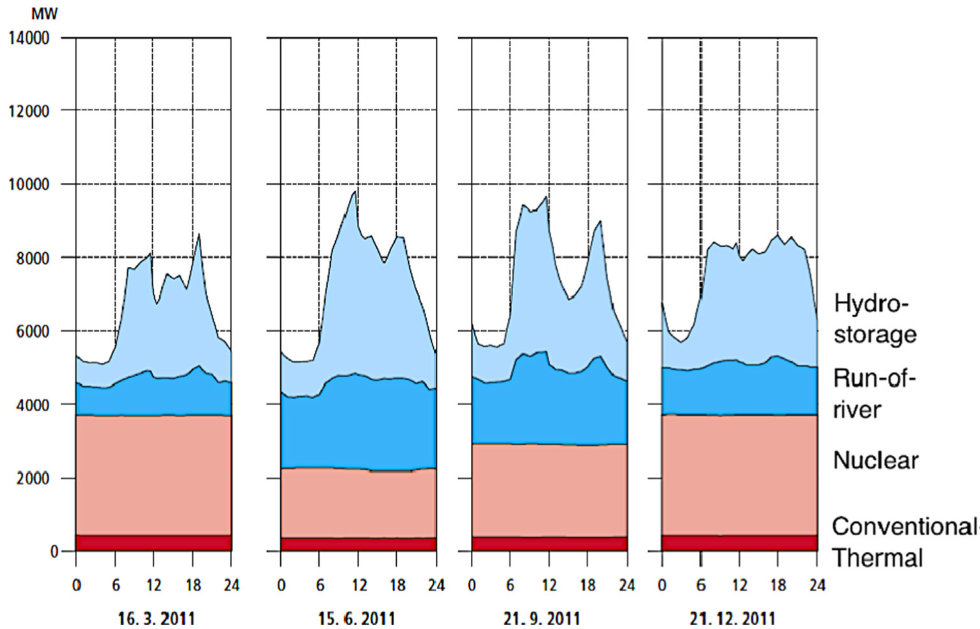

Fig. 6. Electricity generation profile for Switzerland [22].

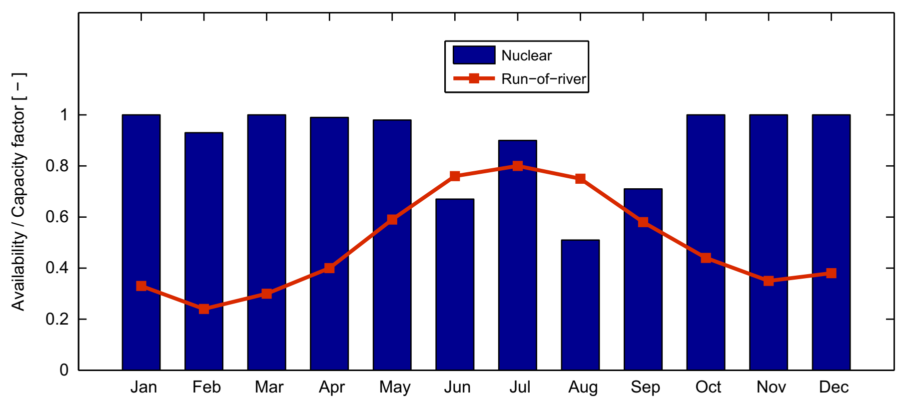

Fig. 7. Seasonal variation of generator (nuclear and run-of-river) capacity factors.

capacity was allotted to the generators using

$$C_i^{fuel} = (TC^{fuel} - G^{fuel})/N^{fuel} \quad (5)$$

where C_i^{fuel} refers to ith generator with '*fuel*' as primary driver, TC^{fuel} is the total installed capacity, G^{fuel} is the known installed capacity of that generation type, and N^{fuel} is the number of generators.

2.4.2. Dispatch model

The generators are ordered in terms of power dispatch using their marginal cost curves and merit order curves for the generation fleet. In our simulations, after having determined the total instantaneous demand for electricity, delivery from generators is accepted in the order of increasing marginal costs. In order to simulate the generators' operation realistically for Switzerland, the historical monthly average power production profile, as shown in Fig. 6, was used to construct pseudo-marginal costs to apply to the model for the power plants in Switzerland. For example, conventional thermal or biomass plants constitute approximately 10% of Switzerland's power production fleet and are operated continuously, generating a fixed portion of the base-load, as shown in Fig. 6. Therefore the marginal costs for such power plants in Switzerland are the lowest when compared to other power generators in Switzerland. The instantaneous cross-border imports (or exports) for the simulation year were used in the model as pseudo-generators (or pseudo-loads) with the lowest marginal costs, in order to force boundary conditions within the model and identify the actual instantaneous power produced by the generators in Switzerland.

Ideally, the marginal cost of hydrostorage plants is determined from the corresponding 'water values', which are a function of a reservoir's level and the time of year. However, in the model the marginal cost for all hydrostorage plants in Switzerland was set higher than all other power generators. Fig. 6 justifies this assumption as most of the load following and peak matching in Switzerland is achieved through hydropower and storage plants.

2.4.3. Variability in generation

Variability in the power generation profiles arises due to various factors, such as variability in demand and exports, seasonal effects, the variable characteristics of renewable generation, downtime for maintenance etc. For example, the power output of a run-of-the-river hydroplant is dependent on the volumetric flow of the river, which for the present work was obtained from the BfE database [13]. Fig. 7 shows a typical monthly volumetric flow; from this variation the availability factors are determined to range from 20% to 80%, and typically peak during the summer months. Similarly, the availability factors for nuclear power plants were also derived from the BfE database [13].

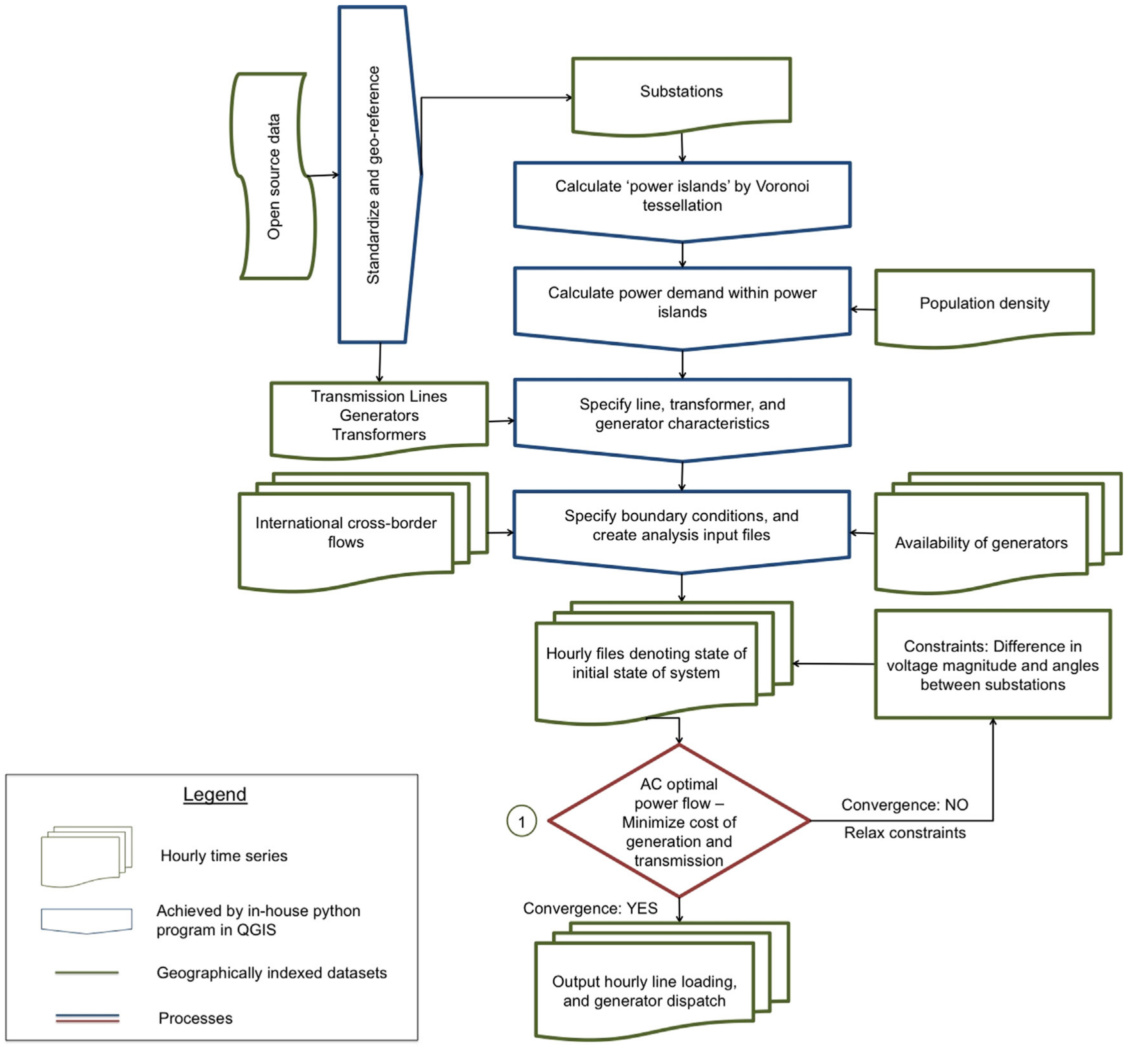

Fig. 8. Schematic highlighting data and processes in a GIS-integrated optimum power flow analysis method.

In practice, the operating nuclear power capacity is significantly reduced during the summer months when nuclear plants undergo maintenance, as can be seen in Fig. 7. Therefore, in the model, the available capacity factors for run-of-the-river hydro and nuclear plants are modelled using spline curve fits to the data. The availability factors for thermal power plants are assumed to be 100%.

The power generated by wind power plants is determined from the time series of simulated wind speeds over a year. For this purpose, the mesoscale model, WRF, was used to simulate wind resource over Switzerland on a grid with horizontal resolution of 5 km $\times$ 5 km [23]. Time series data of wind speeds at geographic locations of wind farms were used in combination with the turbines' power curves to estimate instantaneous power generation from the wind power plants.

2.5. Optimal power flow modelling

The models described above were used to create a geographically indexed operational history of Switzerland's transmission network for the year 2011. The simulations, which yielded the hourly average power flows in transmission lines and the generators' operating capacities were obtained using MATPOWER's AC (alternating current) optimal power flow solver (labelled (1) in Fig. 8) [24]. The optimization minimized the instantaneous cumulative cost of power production in Switzerland, subject to limits on the generators' available capacities, the thermal limits on transmission lines, the constraints on angles and magnitudes of voltage, and the marginal cost of generator operation. The flowchart in Fig. 8 shows the schematic representation of the GIS-integrated approach. The pre-processing of the GIS data was carried out using in-house python subroutines within QGIS [28]. The developed subroutines also post-processed the simulation results for ease of visualization in QGIS.

3. Results and discussion

3.1. Simulated dispatch

In Fig. 9, the simulated production of each generator type is compared to the actual production statistics for 2011 obtained from the Swiss Federal Office of Energy [22]. The accuracy of the simulations is better than 90%, thereby validating the assumptions that are made in the dispatch model and in the modelling of the variability in generation.

3.2. Swissgrid—simulated transmission grid

Fig. 10 shows the simulated mean power flow in each line of Switzerland's transmission network. The power flows are normalized relative to their respective thermal limits. The simulation was carried out with the hourly demand and cross-border flows for the year 2011 as inputs. Therefore, a total of 8760 load flow simulations are made. It

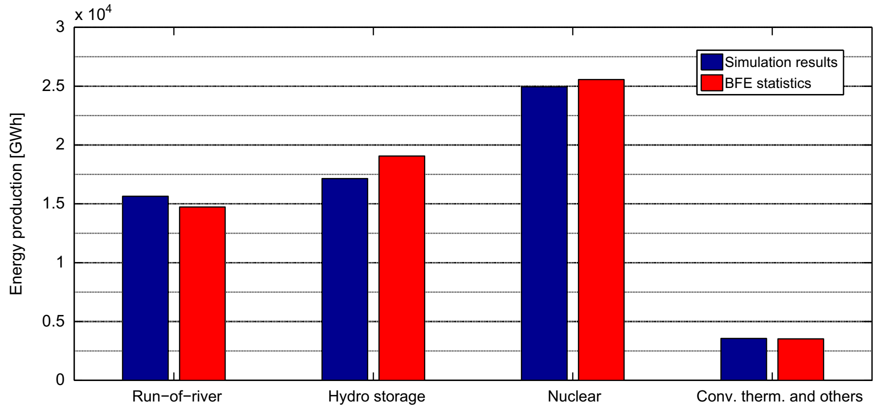

Fig. 9. Comparison of simulated generators' operation based on a merit order curve versus annual BFE statistics.

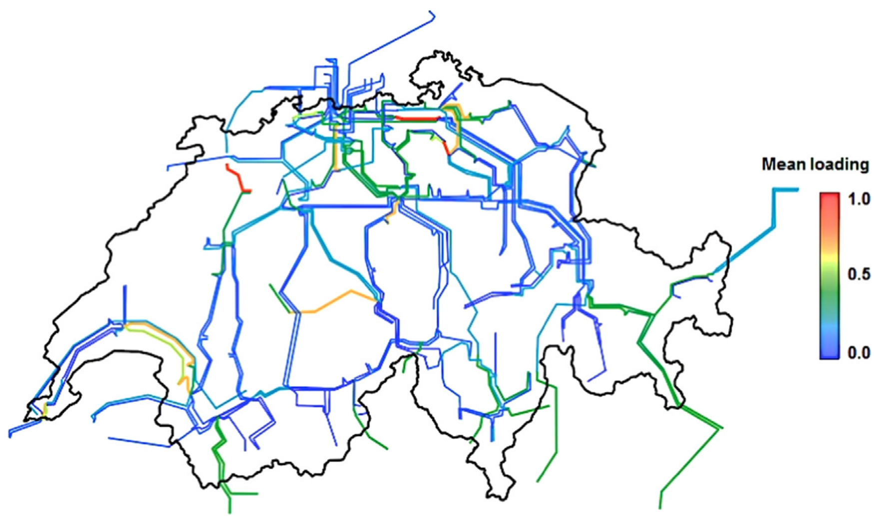

Fig. 10. Normalized annual mean power flow in Switzerland's transmission network.

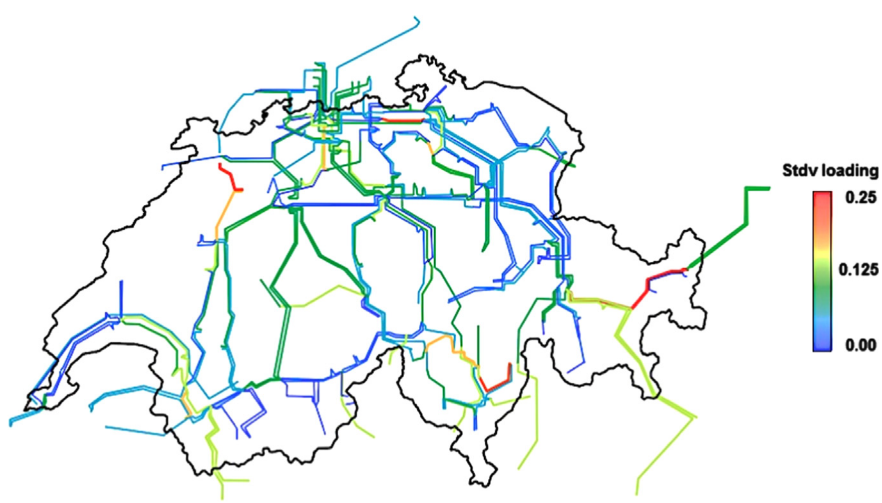

Fig. 11. Normalized annual standard deviation in active power flow in Switzerland's transmission network.

can be seen that the line elements with mean loads greater than 0.6 are identified in northern Switzerland. In particular, one of the 380 kV lines is shown to be operating close to its thermal limit. Other high load lines are observed in central Switzerland. Generally, lower mean load lines (below 0.2) are observed in the Alpine region of lower central Switzerland; this is because the lines in this region transport large amounts of hydro-generated power for only a few hours in a day, and the lines are otherwise not significantly loaded.

Fig. 11 shows the simulated standard deviation of power flow. The standard deviations are normalized with respect to mean power flow. Fluctuations in the Swiss power grid arise from two sources: (1) scheduled changes in generation patterns as hydro-generated

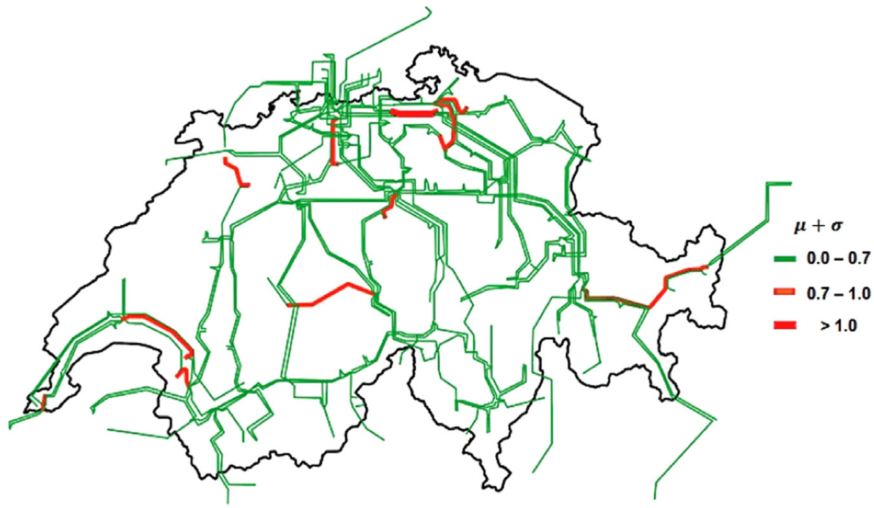

Fig. 12. Criticality factor in Switzerland's transmission network based on a transmission reliability margin of 30%.

Table 5
Lengths of identified critical circuit elements.

Voltage level	$0.7<\mu+\sigma<1.0$	$\mu+\sigma>1.0$	Total
220 kV	235 km	0 km	235 km
380 kV	80 km	20 km	100 km
Total	315 km	20 km	335 km

power is ramped up or down as a consequence of daily and seasonal demand variations, and (2) variation in cross-border power flows. High fluctuations are therefore observed in the Alps where large hydro-storage plants are connected to the grid, and in the majority of the lines connecting Switzerland to Italy. The largest standard deviation is of the order of 0.25 for a line in eastern Switzerland close to the border with Austria. Generally, lower fluctuations are observed in the majority of 380 kV lines as these are mostly used for less volatile power transit from North to South.

3.3. Critical operating limit

To detect 'critical' line elements in the transmission network, a criterion called 'criticality factor' is introduced, that accounts for both the annual mean and the variability in loading of the line. The 'criticality factor' is defined as the sum of the mean and standard deviation of active power flows, normalized by the thermal limit. In order to meet ENTSOE's operational regulations for grid security, following the work of the dena Grid Study II [4], a constant transmission reliability margin of 30% was used; this approach differs from an alternative approach of $(N-1)$ contingency analysis that is used by utilities. Transmission line elements with a criticality factor greater than 0.7 are identified as 'critical'. Fig. 12 shows the criticality factors across the Switzerland's transmission system for the year 2011. As summarized in Table 5, a total of 12 line elements with a cumulative length of 335 km are identified as critical.

3.4. Predicting grid expansion plans

In order to guarantee the long-term reliability of electricity supply in Switzerland, Swissgrid has defined 8 priority programmes that must be implemented for the expansion of the transmission network [25]. Fig. 13 compares Swissgrid's expansion plan with the present analysis. In the present analysis the lines with a minimum loading of 55% are shown. Highlighted in yellow are the commonly identified lines across the two analyses. A good agreement between the two sets of results can be seen. 7 out of Swissgrid's 8 priority expansion projects are either partially or completely identified. It should be noted that the Swissgrid expansion plan calls for the construction of new lines, in addition to the upgrading of several existing 220 kV lines to 380 kV lines. The differences between the two analyses are due to the fact that our power flow analysis does not account for non-existent lines.

3.5. Switzerland's grid—scenario-2020 wind power

The impact of increased wind power production on the Swiss transmission system is examined next. Besides existing power plants, new wind power plants with a cumulative installed capacity of 850 MW, worth 5% of the total installed production capacity, are projected to exist in Switzerland's 2020 test scenario. For the purpose of power flow simulations for the year 2020, gross electricity demand is extrapolated based on the last 10 years of historical data; this extrapolation yields an increase of 12% in demand compared to the year 2011. All other grid model input parameters are kept unchanged from the 2011 case. For the 2020 scenario, a portfolio of wind power plants was identified using our in-house developed GIS-tool, wind-Seeker. The energy production of the wind power plants is based on mesoscale model simulations of wind resources across Europe (Fig. 14) and financial performance is used to identify the portfolio of wind power plants with a total installed capacity of 850 MW. The identified projects were then aggregated into hexagonal-shaped development zones (Fig. 14 (inset)) on the basis of installed capacity. In the power flow simulations, wind-generated electricity was then injected into the transmission network at the locations of development zones, using the time series of simulated wind speed.

Fig. 15 shows the mean and standard deviation of the active power flow for selected lines with and without wind power introduced into the grid. The selected lines in the southern region of Switzerland are also shown in Fig. 15. There is a substantial increase in the mean and standard deviation of the power flows due to introduction of wind into the transmission system. However, these power flows remain well below the critical line-loading limit of 70% (mean plus one standard deviation power flow shown as the red line in Fig. 15 (top)) for all lines.

It can therefore be deduced that the grid infrastructure in southern Switzerland is sufficient to cope with the increased power flows associated with wind energy production in the 2020 scenario. Furthermore, the results reveal that for a few lines, for example for line elements numbered 66 and 114 in Fig. 15

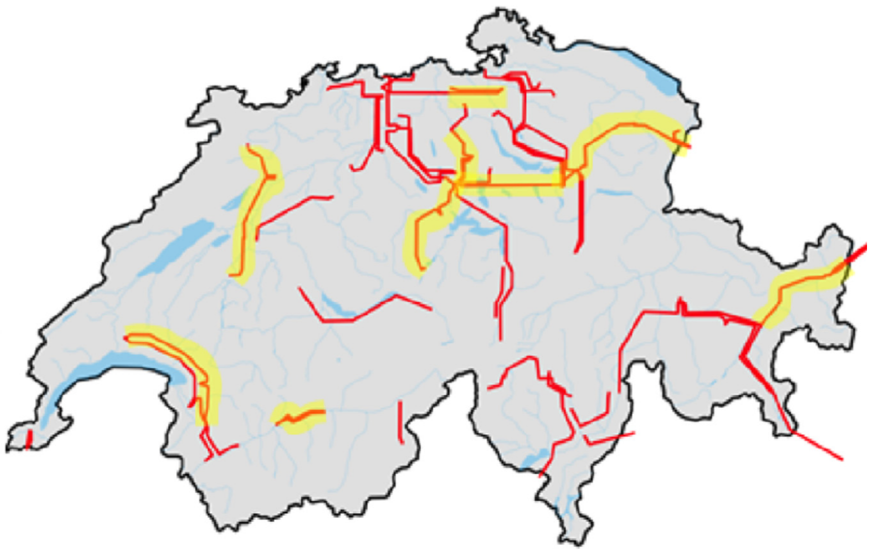

Fig. 13. Lines identified for upgrade from simulations in red; lines common to Swissgrid expansion plan are highlighted in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

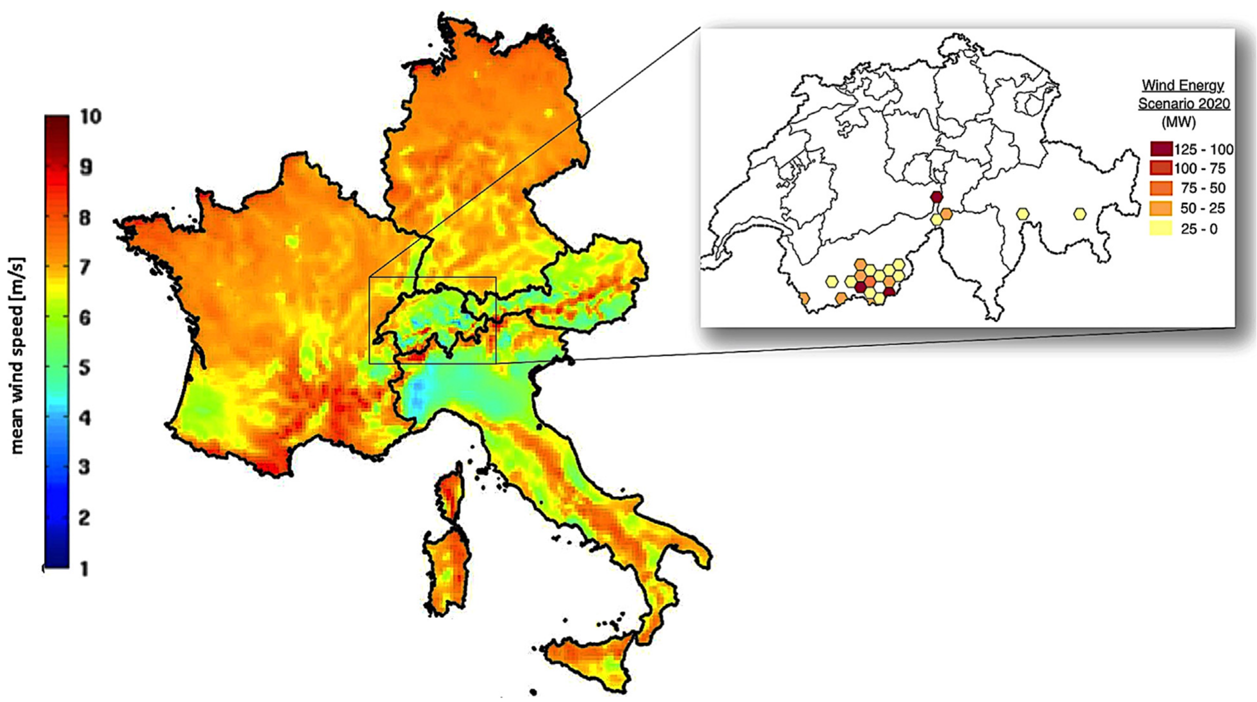

Fig. 14. Annual mean wind speed at a height of 80 m above the ground for Switzerland and its neighbors (Germany, Austria, Italy and France); (inset) locations of development zones of wind power plants to meet Switzerland's 2020 scenario of renewable energy.

(top), the mean power flow is reduced after the introduction of wind power. This demonstrates that changes in the power flow due to injection of local power are not intuitively deterministic and depend on the state of the grid in the neighborhood of the power injection.

4. Conclusion

The lack of information about power systems makes it difficult to analyze and benchmark power flow studies of a system. Using Switzerland as a test case, this paper presents a detailed methodology for the approach of geographically indexed production, demand and grid modelling of large area power systems. Validation of the developed model with analyses of Swissgrid is provided and a good agreement was observed; simulations identified 7 out of 8 transmission corridors marked for grid-expansion by Swissgrid. The versatility of the approach to grid-assessment for the development of wind power in Switzerland was examined for the year 2020 scenario. It is shown that Switzerland's grid in the regions of increased wind energy is capable in its current state of providing a congestion-free dispatch. This approach can therefore be used to assess grid capacity for the development of future projects.

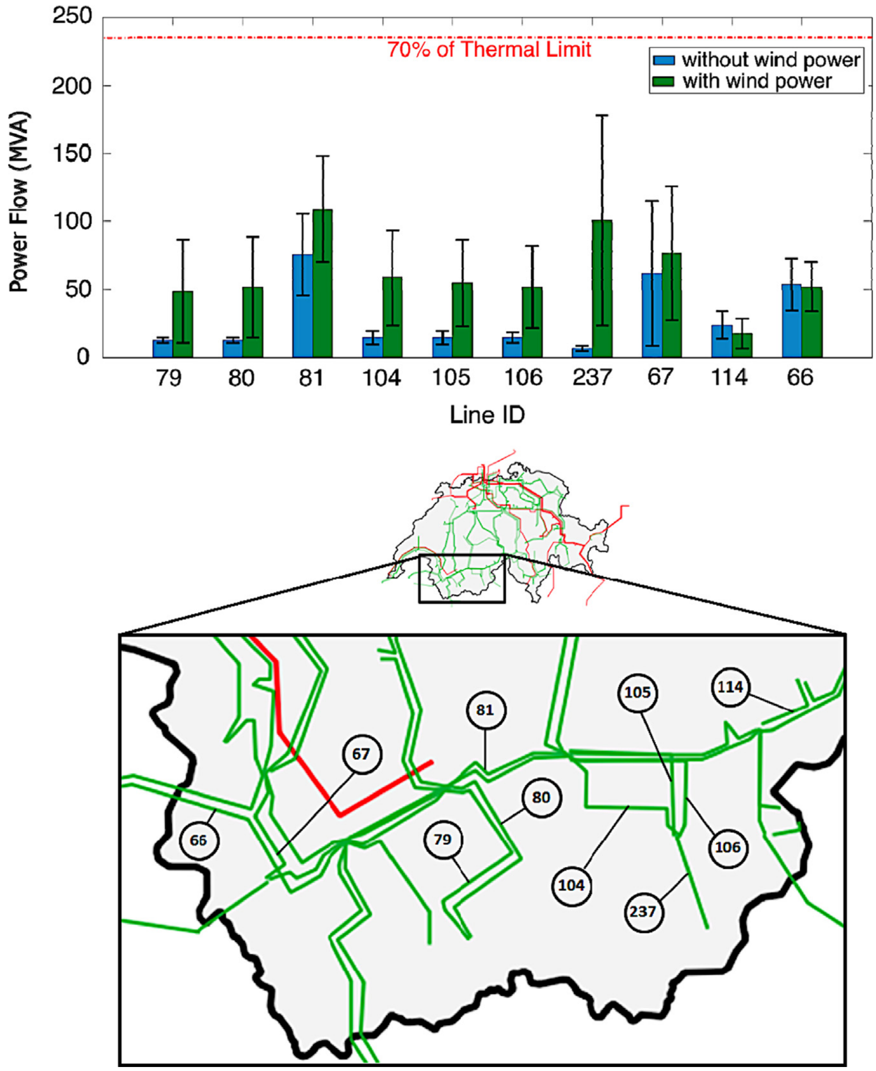

Fig. 15. Increase in mean and standard deviation in active power flow for the year 2020 (top); transmission network in the south of Switzerland (bottom). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

References

[1] Zhou Q, Bialek J. Approximate model of European interconnected system as a benchmark system to study effects of cross-border trades. IEEE Trans Power Syst 2006;20(2):782–8.

[2] Hagspiel S, et al. Copula-based modeling of stochastic wind power in Europe and implications for the Swiss power grid. Appl Energy 2011;96:33–44, http://dx.doi.org/10.1016/j.apenergy.2011.10.03996.

[3] Hagspiel S. Impact of stochastic wind energy on Switzerland's power grid [Master thesis]. Power Systems Laboratory, ETH Zurich; 2011. Available at: ⟨http://www.eeh.ee.ethz.ch/uploads/tx_ethpublications/MA_Simeon_Final_Report.pdf⟩ [accessed: June 2012].

[4] German Energy Agency. Dena grid study-II: integration of renewable energy sources into German power supply system in the 2015–2020 period with outlook for 2025. Final Report, Berlin, Germany, 2010. Available at: ⟨http://www.dena.de/en/projects/renewables/dena-grid-study-ii.html⟩ [accessed: January 2012].

[5] Parsons B, Milligan M. Grid impacts of wind power variability: recent assessments from a variety of utilities in the United States. Springfield, Virginia, USA: National Renewable Energy Laboratory; 2006 (NREL/CP-500-39955).

[6] European Energy Exchange. Available at: ⟨www.eex.com⟩ [accessed: February 2013].

[7] Zimmermann RD, Murillo-Sanchez CE, Thomas RJ. MATPOWER: steady-state operations, planning, and analysis tools for power systems research and education. IEEE Trans Power Syst 2011;26(1):12–9.

[8] Singh A, Wolff F, Chokani N, Abhari RS. Optimizing synergy of utility-scale wind and pumped-hydro storage. IGTI Turbo Expo 2013. ASME GT2 013-96034, San Antonio, USA; 2013.

[9] Willi D. Econometric assessment of wind energy in Poland. Zürich, Switzerland: ETH Zürich; 2012 (Laboratory for Energy Conversion: Internal Report).

[10] Wolff F. Forecasting wind energy outlook for Germany and econometric assessment of pumped-hydro energy storage to reduce wind power variability [Master thesis]. ETH Zurich, Zürich, Switzerland; 2012.

[11] Singh A, Chokani N, Abhari RS. Large area assessment of transmission capacity for wind power dispatch. In: Proceedings of the German wind energy conference DEWEK. Bremen, Germany; 2012.

[12] European Network of Transmission System Operators for Electricity ENTSO-E. Available at: ⟨www.entsoe.eu⟩ [accessed: January–November 2012].

[13] Swiss Federal Office of Energy SFOE. Overall Energy Statistics. Available at: ⟨www.bfe.admin.ch⟩ [accessed: December 2012].

[14] Kron G. Tensorial analysis of integrated transmission systems, part-III. Trans Am Inst Electr Eng 1952;71(1):814–22.

[15] Swissgrid. Grid Development. Available at: ⟨www.swissgrid.ch/grid/development⟩ [March 2012].

[16] Andersson G. Power Systems Laboratory. Lecture notes. ETH Zurich, Zurich, Switzerland; 2012.

[17] ENTSO-E, Grid maps. Available at: ⟨https://www.entsoe.eu/publications/grid-maps/⟩ [accessed: March 2012].

[18] Thomas R Markets for reactive power and reliability: a white paper. Engineering and Economics of Electricity Research Group, Cornell University, 2006.

[19] Centre for International Earth Science Information Network (CIESIN). Socioeconomic Data and Applications Centre (SEDAC). 2010. Gridded Population of the World (GPW), Version 3. Palisades, NY: CIESIN, Columbia University. Available at ⟨http://sedac.ciesin.columbia.edu/data/collection/gpw-v3⟩ [accessed: June 2012].

[20] Swiss Federal Statistical Office. Available at: ⟨www.bsf.admin.ch⟩ [accessed: June 2012].

[21] Swissgrid. Energy Data. Available at: ⟨http://www.swissgrid.ch/swissgrid/en/home/reliability/energydata⟩ [accessed: November 2012].

[22] BfE. Grafiken der Elektrizitätsstatistik, 2011. Available at: ⟨www.bfe.admin.ch⟩ [accessed: February 2012].
[23] Jafari S, Sommer T, Chokani N, Abhari RS. Wind resource assessment using a mesoscale model: the effect of horizontal resolution. In: Proc. ASME Turbo Expo 2012. GT2012-69712; 2012.
[24] Zimmermann RD, Murillo-Sanchez CE, Thomas RJ. MATPOWER's extensible optimal power flow architecture. In: Proceedings of the IEEE power and energy society general meeting; 2009, 1–7.
[25] Swissgrid, Grid Expansion. Available at: ⟨www.swissgrid.ch/grid/gridexpansion⟩ [accessed: December 2012].
[26] Dutton G. In: Proceedings of the first international advanced symposium on topological data structures for GIS. Harvard University, Cambridge, MA, USA. Vol. 8; 1978.
[27] Gold CM. Problems with handling spatial data—the Voronoi approach. CISM J 1991;45(1):65–80.
[28] QGIS Development Team. QGIS geographic information system. Open Source Geospatial Foundation Project. Available at: qgis.org [accessed: February 2013].